# 2005 Annual Project Summary Refining slip rates and earthquake recurrence times along the San Andreas fault using geodetic data and 3D viscoelastic cycle models

**External Award Number 05HQGR0127**

Kaj M. Johnson
Department of Geological Sciences
Indiana University
1001 E. 10th St.
Bloomington, IN 47405
kajjohns@indiana.edu
and
Paul Segall
Geophysics Department
Stanford University
Stanford, CA 94305
segall@pangea.stanford.edu

## Investigations Undertaken

To date, probabilistic earthquake forecasts have relied heavily on paleoseismic data, with only limited input from mechanical models and measurements of strain accumulation. This is in large part due to the fact that geodetic strain measurements are often interpreted using overly simplified elastic dislocation models. We are in the process of developing 3D viscoelastic cycle models for the San Francisco Bay area in order to both test more sophisticated plate boundary loading models and to use geodetic data to refine geologic estimates of fault slip rates and average earthquake recurrence times. The model consists of faults in an elastic lithosphere overlying a viscoelastic asthenosphere. The effect of all past earthquakes is incorporated by modeling earthquakes as periodic slip events at specified recurrence intervals. The analytical form of the solution allows for complete nonlinear inversion for the posterior distribution of the slip rates, recurrence times, thickness of the lithosphere, and viscosity of asthenosphere. The strategy is to implement Bayesian inversions of the geodetic data with *a priori* probability distributions on the parameters adopted from geologic and paleoseismic data. We use a Monte Carlo-Metropolis method to efficiently sample the joint posterior probability distribution of slip-rates, recurrence times, elastic thickness, and asthenosphere viscosity.

The major active faults in the Bay area are segmented into planar faults modeled as uniform slip dislocations. The slip-rate and recurrence times are estimated on each of the fault segments. We anticipate this approach will allow us to improve our knowledge of the distribution of slip rates and greatly reduce the uncertainty in existing estimates of recurrence times in the San Francisco Bay and Carrizo Plain/Big Bend areas.

# Results

This project is just under-way and there are no preliminary results to report from the 3D modeling. To date, we have derived 3D viscoelastic solutions using propagator matrix formulations, implemented in Matlab scripts. We have obtained all historical triangulation data for the San Francisco Bay area from the National Geodetic Survey. We will use the triangulation data to calculate the evolution of strain rate over time. Results from a separate study we are conducting in the Mojave region of southern California shows that it is important to have deformation measurements spanning a broad interval of time in order to resolve the viscous structure of the lithosphere.

In this work we are extending the approach of Johnson and Segall [2004] to 3D. In this previous study, we used geodetic data and viscoelastic cycle models to refine the slip rates and to estimate recurrence times independently of paleoseismic data. The results from Johnson and Segall [2004] are summarized in Table 1. The uncertainties in slip rate are smaller than those in the other geodetic studies, and the ranges for recurrence times are narrower than in WGCEP [2002]. This study shows that the geodetic data can indeed contribute to the estimates of San Francisco Bay area slip rates and recurrence times if the problem is formulated in a Bayesian sense using the geologic data as prior information. However, the viscoelastic cycle models we used in Johnson and Segall [2004] are limited by the assumption of two-dimensional deformation with infinitely long, parallel faults which may not be a good approximation for the Bay area. To remove this limitation we are developing 3D viscoelastic cycle models for the San Francisco Bay area in this project.

| | model | SA slip rate | SA recurrence | RC/H slip rate | RC/H recurrence | GV slip rate |
|---|---|---|---|---|---|---|
| Prescott et al. [2001] | elastic dislocation | 17-24.6 | | 4.9-15.7 | | 3.7-12.5 |
| Murray et al. [2001] | elastic dislocation | 14.7-22.9 | | 5.8-17.8 | | 2.8-10.8 |
| Freymueller et al. [1999] | elastic dislocation | 11.8-23 | | 7.1-20.7 | | 4.2-12.2 |
| Johnson and Segall [2004] | viscoelastic cycle | 20.2-27 | 200-300 | 10.2-13 | 525-700 | 8.0-8.0 |
| WGCEP [2002] | | 21-27 | 180-370 | 7-11 | 235-710 | 2-8 |

To model deformation in the San Francisco Bay area, we will separate all the major active faults into segments that will be approximated with uniform slip dislocations (Figure 2). As a starting point, we will model the upper part of the fault as locked between earthquakes with steady creep on the lower part of the fault. In these initial models slip will be modeled kinematically, without any response to stresses acting on the faults.

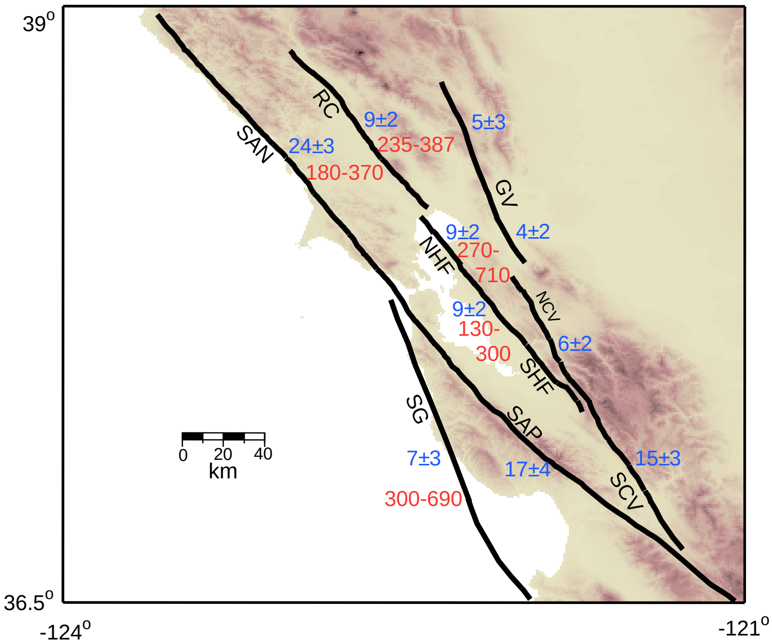


Figure 1: Summary of slip rates and recurrence intervals in the San Francisco Area adopted by Northern California Working Group on Earthquake Probabilities(WGCEP [2002]). Slip rates in blue (mm/yr), recurrence times in red (years). SAN – San Andreas northern segment, RC – Rodgers Creek fault, GV – Green Valley fault, SG – San Gregorio fault, SAP – San Andreas Peninsula segment, NHF – Northern Hayward fault segment, SHF – Southern Hayward fault segment, NCV – Northern Calaveras segment, SCV – Southern Calaveras segment.

Numerous scenarios can be imagined for segmenting the San Francisco Bay faults. We will begin with perhaps the simplest scenario in which characteristic earthquakes are assumed based on recent earthquake history. The M = 7.7 1906 San Francisco earthquake ruptured 470 km of the San Andreas fault including the entire section of the fault in the San Francisco Bay area. About 40 km of the southern Hayward fault (green line, Figure 2) ruptured in an 1868 M = 7.0 earthquake. The exact location of a large earthquake in 1838 is not known unequivocally, but is believed to have occurred on the Peninsula segment of the San Andreas fault. Differing studies suggest magnitudes ranging from 6.8-7.5 for this event. There are also numerous earthquakes with magnitude less than 7 in the historical record. In this simple scenario it will be assumed that the $M > 7$ earthquakes in the historical record are characteristic events that occur periodically.

Figure 2 shows the configuration of fault geometry and segmentation for this scenario. Each fault segment will be modeled with a single dislocation with its own recurrence time and uniform slip rate. The San Andreas fault is divided into three segments: The northern San Andreas, which ruptures in 1906 type events, the San Andreas Peninsula segment, which ruptures in 1906 events and 1838 type events, and the southern segment that creeps all depths. Based on previous studies, the Hayward fault is subdivided into fully creeping (blue) and partially creeping sections (green). Based on various paleoseismic and geodetic studies of the Calaveras fault cited in WGCEP [2002], the Calaveras fault is divided into a northern fully locked segment and a southern segment that creeps at the surface. Lacking segmentation information from historical events, the Rodgers Creek, San Gregorio, and Green Valley faults are modeled as single segments. This scenario results

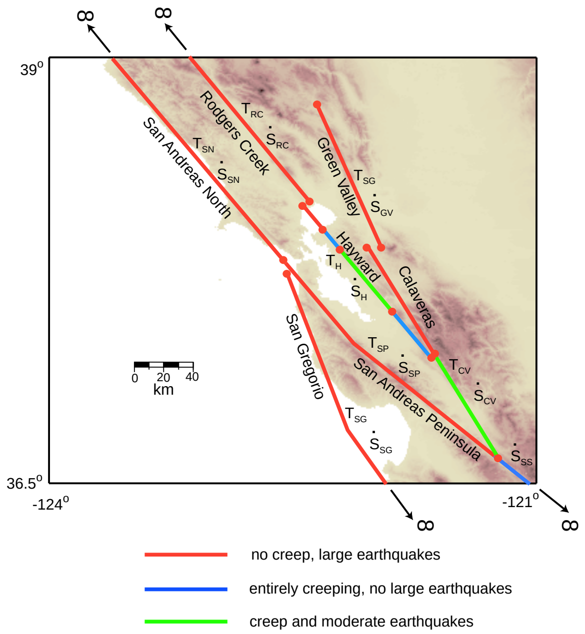


Figure 2: Candidate model fault geometry and parameters to estimate. Red dots denote endpoints of straight fault segments to be modeled with uniform dislocations.

in 9 unknown slip rates and 8 unknown recurrence times (Figure 2). It makes sense to place a simple kinematic condition on the long-term slip rates to prevent discontinuities across intersections of fault segments, as is done in the elastic block models discussed in the introduction. Requiring the sum of slip rates on the branches of a fault to be equal to the slip rate on the "stem" of the fault reduces the number of slip rate estimates by five, reducing the total number of unknowns to twelve.

Other segmentation scenarios could be tested for consistency with the geodetic and geologic data. For example WGCEP [2002] considers various rupture scenarios including the possibility of the Rodgers Creek segment rupturing at the same time as the Hayward fault, both segments of the Calaveras fault rupturing at the same time, and the San Andreas segments rupturing in separate events. Some scenarios could contain a distinct Loma Prieta source, for example. We will determine whether the various scenarios produce distinctively different deformation patterns that can be tested against the data.

# Reports Published


Johnson, K.M., and Segall, P. 2004. Viscoelastic earthquake cycle models with deep stress-driven creep along the San Andreas Fault system, Journal of Geophysical Research, 109, B10403, doi:10.1029/2004JB003096.

Johnson, K.M., and Segall, P. 2004. Toward 3D viscoelastic earthquake cycle models for the San Francisco Bay area, 2004 SCEC Annual Meeting, poster presentation.

# Non-technical Summary

We are developing 3D viscoelastic cycle models for the San Francisco Bay area in order to use geodetic data to refine geologic estimates of slip rates and recurrence times. The strategy is to design Bayesian inversions of the geodetic data with *a priori* probability distributions on the parameters adopted from geologic and paleoseismic data. The 3D viscoelastic cycle model is being applied to the San Francisco Bay area assuming the major faults can be segmented into planar faults modeled as uniform slip dislocations for which we are estimating the slip rate and recurrence time for each fault segment.